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Targeting key alteration minerals in epithermal deposits in Patagonia, Argentina, using ASTER imagery and principal component analysis

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Abstract. Principal component analysis (PCA) is an image processing technique that has been commonly applied to Landsat Thematic Mapper (TM) data to locate hydrothermal alteration zones related to metallic deposits. With the advent of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), a 14-band multispectral sensor operating onboard the Earth Observation System (EOS)-Terra satellite, the availability of spectral information in the shortwave infrared (SWIR) portion of the electromagnetic spectrum has been greatly increased. This allows detailed spectral characterization of surface targets, particularly of those belonging to the groups of minerals with diagnostic spectral features in this wavelength range, including phyllosilicates ('clay' minerals), sulphates and carbonates, among others. In this study, PCA was applied to ASTER bands covering the SWIR with the objective of mapping the occurrence of mineral endmembers related to an epithermal gold prospect in Patagonia, Argentina. The results illustrate ASTER's ability to provide information on alteration minerals which are valuable for mineral exploration activities and support the role of PCA as a very effective and robust image processing technique for that purpose.

1. Introduction

Spectral identification of potential areas of hydrothermal alteration minerals is a common application of remote sensing to mineral exploration. The extraction of spectral information related to this type of target from Landsat Thematic Mapper (TM) imagery has been achieved through the use of image processing techniques such as band ratioing and principal component analysis (PCA) (Sabine 1999).

With the limited spectral resolution provided by Landsat TM, alteration mapping has been restricted to the detection of areas where alteration processes are likely to have occurred—the TM visible and near-infrared (VNIR) and shortwave infrared (SWIR) bands are only able to discriminate areas rich in iron oxides/

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hydroxides and clay and carbonate minerals, respectively. However, with the spectral resolution provided by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), identification of specific alteration assemblages becomes feasible, since it has six spectral bands in the SWIR (bands 4–9) (Abrams 2000), a region where many clay and carbonate minerals show diagnostic spectral features, compared to only two TM bands (TM5 and TM7).

In this Letter, the capability of ASTER bands to discriminate alteration minerals related to an epithermal gold prospect in northern Patagonia, Argentina, using a simple, yet robust, image processing technique to produce mineral abundance maps from ASTER bands, is demonstrated.

2. Background

Most of the variation of radiant spectral flux measured by a sensor depends on topographic shading and albedo effects at the surface. PCA is a powerful statistical technique that can be used for suppressing irradiance effects that dominate all bands, therefore enhancing spectral reflectance features of geological materials. PCA can be applied to multivariate datasets, such as multispectral remote sensing images, with the purpose of extracting specific spectral responses, as in the case of hydrothermal alteration minerals.

Crósta and Moore (1989) developed a technique based on PCA for mapping iron oxide/hydroxides related to sulphide ore bodies in granite–greenstone belt terrains using Landsat TM. The technique, called 'feature-orientated principal component selection' (FPCS), relied on establishing the relationship between the spectral responses of target materials (ferric-oxide-rich soils) and numeric values extracted from the eigenvector matrix used to calculate the principal component (PC) images. Using this relationship, they were able to determine which PCs contained the spectral information due to iron minerals and whether the digital numbers (DNs) of pixels containing the target materials had high (bright) or low (dark) values.

Loughlin (1991) modified the FPCS technique by selecting specific Landsat TM band sets and applying PCA separately to them, to ensure that certain materials (e.g. vegetation) would not be mapped and that spectral information due to target materials (alteration minerals) would be mapped into a single PC. The procedure proposed by Loughlin used Landsat TM band sets comprising bands 1, 3, 4 and 5 for deriving spectral information related to ferric oxides/hydroxides, which would be uniquely mapped into either PC3 or PC4. Another band set, comprising bands 1, 4, 5 and 7, was similarly used to derive information related to hydroxyl-bearing minerals and carbonates, also uniquely mapped into either PC3 or PC4.

This procedure, coined by Loughlin (1991) the 'Crósta technique', has been successfully used for mineral exploration purposes due to its ease of use and robustness (Bastianelli *et al.* 1993, Davidson *et al.* 1993, Ruiz-Armenta and Prol-Ledesma 1998, Souza Filho and Drury 1998, Tangestani and Moore 2001, 2002, Carranza and Hale 2002). In regions subject to mineral exploration and with favourable conditions (sparse or no vegetation, exposed bedrock, etc.), such as in the South American Cordillera, this technique has become a standard operational tool for alteration mapping using Landsat TM.

The idea of applying PCA to derive mineral abundance maps using high spectral resolution data was proposed by Crósta *et al.* (1996) and Prado and Crósta (1997). They used 24-band Geoscan data, covering the VNIR, SWIR and thermal infrared (TIR) portions of the electromagnetic spectrum (a similar spectral coverage to that provided by ASTER), to produce abundance images of hematite, goethite, calcite–chlorite, muscovite–sericite–kaolinite and silica concentrations, related to gold mineralization in hydrothermally altered greenstone belt rocks.

3. Los Menucos gold prospects

Los Menucos region is located in the northern portion of Patagonia, Argentina, where epithermal gold mineralization, related to hydrothermally altered Triassic–Jurassic acidic to intermediate volcanics (Cucchi *et al.* 1999), is currently the focus of exploration efforts. Cerro Abanico and Cerro La Mina are the known largest prospects, located within a NE–SW oriented half-graben some 40 km long by 10 km wide. At Cerro Abanico, quartz and quartz–adularia veins cut dacitic to rhyolitic ignimbrites, sediments and tuffs. Alteration assemblages are typically quartz–illite and pyrite. At Cerro La Mina, alteration minerals include both, high- and low-sulphidation assemblages, comprising kaolinite, alunite, illite–muscovite, dickite, quartz and adularia and have affected a sequence of andesite to rhyolite lava domes. Mineralization is hosted in breccias.

4. ASTER data

ASTER is a joint development between the United States and Japan, with a strong focus on geological and mineral exploration applications. The sensor has 14 spectral bands—three in the VNIR (0.52–0.86 μm) with 15-m spatial resolution, six in the SWIR (1.60–2.43 μm) with 30-m resolution, and five in the TIR (8.125–11.65 μm) with 90-m resolution (Abrams 2000). Of particular interest to alteration mineral mapping are the SWIR bands, located at wavelength intervals where numerous 'clay' (alteration) minerals exhibit diagnostic spectral features (Rowan and Mars 2003).

5. Mineral endmember identification using PCA of ASTER bands

PCA was applied to subsets of four ASTER bands, using an adaptation of the Crósta technique proposed by Loughlin (1991). The subsets were selected according to the position of characteristic spectral features of key alteration mineral endmembers (table 1) in the VNIR and SWIR portions of the spectrum.

After applying PCA, the eigenvector matrix used to calculate PCA for each subset was examined, to identify which PC contained the target (mineral) information. The criterion for the identification is the same proposed by Loughlin (1991): the PC that contains the target spectral information shows the highest eigenvector loadings from the ASTER bands, coinciding with the target's most diagnostic

Table 1. ASTER bands (VNIR + SWIR) used to generate mineral abundance maps in the Los Menucos area through PCA. Wavelength ranges (in μm) are: band 1, 0.520–0.600; band 3, 0.760–0.860; band 4, 1.600–1.700; band 5, 2.145–2.185; band 6, 2.185–2.225; band 7, 2.235–2.285; and band 9, 2.235–2.285.

	Alteration minerals			
	Alunite	Illite	Kaolinite + smectite	Kaolinite
ASTER bands	1	1	1	1
	3	3	4	4
	5	5	6	6
	7	6	9	7

Table 2. Eigenvector statistics for ASTER bands 1, 4, 6 and 7. This band set was selected for identifying spectral response from kaolinite. PC4 will depict the pixels likely to contain kaolinite due largely to the spectral contrast between bands 4 and 6, minimizing spectral response from other surface materials.

	PC1	PC2	PC3	PC4
Band 1	0.667	−0.722	0.179	−0.039
Band 4	0.441	0.384	−0.258	−0.769
Band 6	0.443	0.217	−0.648	0.580
Band 7	0.406	0.532	0.694	0.266

features, but with opposite signs (+ or −). For example, kaolinite has high reflectance values in ASTER bands 4 and 7 and absorbs strongly in bands 1 and 6; the PCA eigenvector statistics of these bands (table 2) shows that PC4 has a high and negative loading from band 4 (−0.769) and high and positive loading from band 6 (0.580), indicating that pixels likely to contain kaolinite will be represented by low (dark) DN values in PC4. Loadings for bands 1 and 7 show significantly lower values (−0.039 and 0.266, respectively), indicating that the relevant spectral

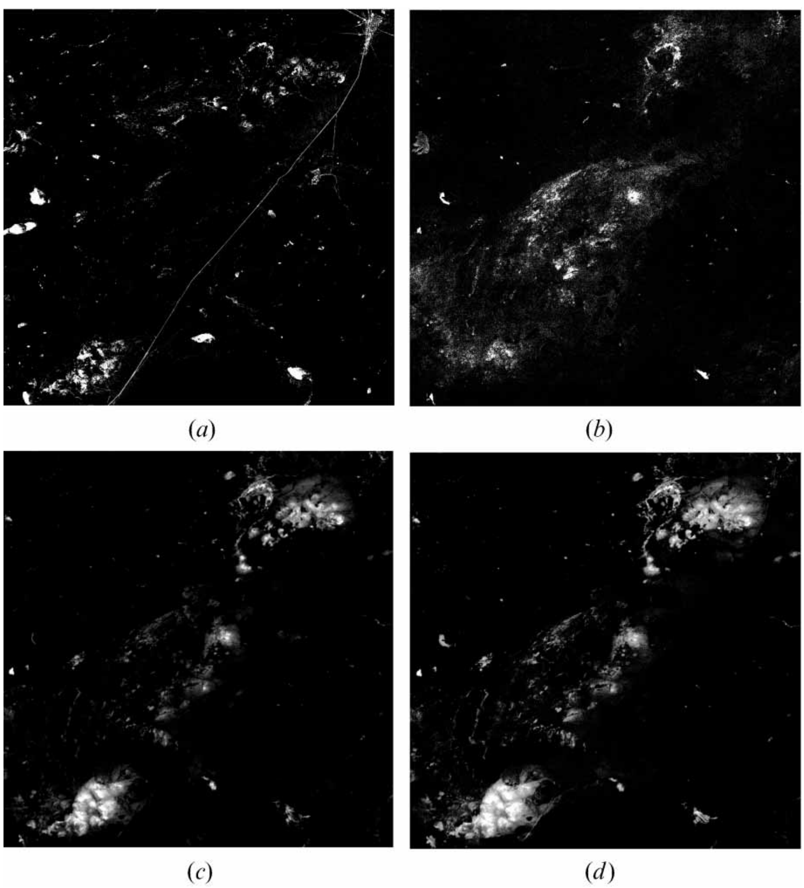

Figure 1. Abundance images of Los Menucos for (*a*) alunite, (*b*) illite, (*c*) kaolinite/smectite and (*d*) kaolinite, produced using PCA of ASTER bands. The images are approximately 30 km across.

information will be shown by the spectral contrast of kaolinite in the wavelength positions equivalent to bands 4 and 6. To facilitate visualization, the PC4 image is then negated (by multiplying all pixels by −1), so that the target material is displayed as bright pixels in the respective abundance image (figure 1(*d*)).

Mineral abundance images of Los Menucos were produced from ASTER bands using PCA, each one showing areas most likely to contain the alteration minerals listed in table 1. These abundance images are shown in figure 1, with bright DN values indicating high abundances.

A red, green, blue (RGB) colour composite of abundance images for kaolinite, illite and alunite is presented in figure 2, draped over ASTER band 3. All the altered areas known in the Los Menucos district are distinctively represented in this image in different colours.

These results were checked against field spectroscopy data on three selected sites, whose locations are shown in figure 2 as P1, P2 and P3. At each site, a number of spectral measurements were taken using a PIMA (Portable Infrared Mineral Analyzer) reflectance spectrometer. An average spectrum was produced for each site and then classified with reference to the US Geological Survey (USGS) mineral spectra library using the Spectrometer Independent Mineral Identification Software (SIMIS) spectral analysis package (Mackin 2002). Figure 3 presents the results of the spectral analysis, which identified the major mineral component at P1 as being

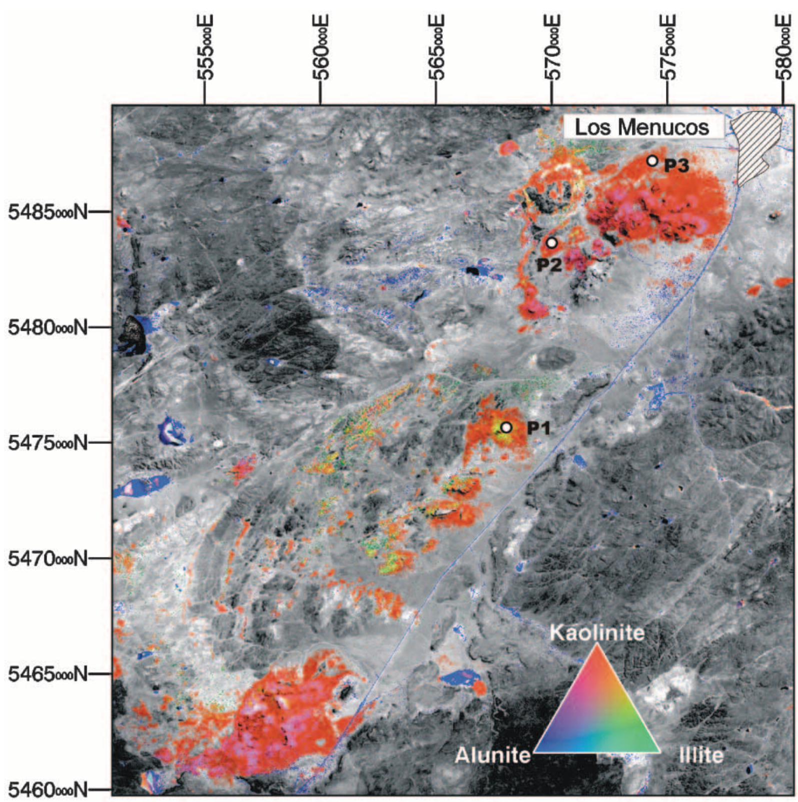

Figure 2. Colour composite of abundance images for kaolinite, illite and alunite in RGB, draped over ASTER band 3. The village of Los Menucos is at the upper right corner of the scene.

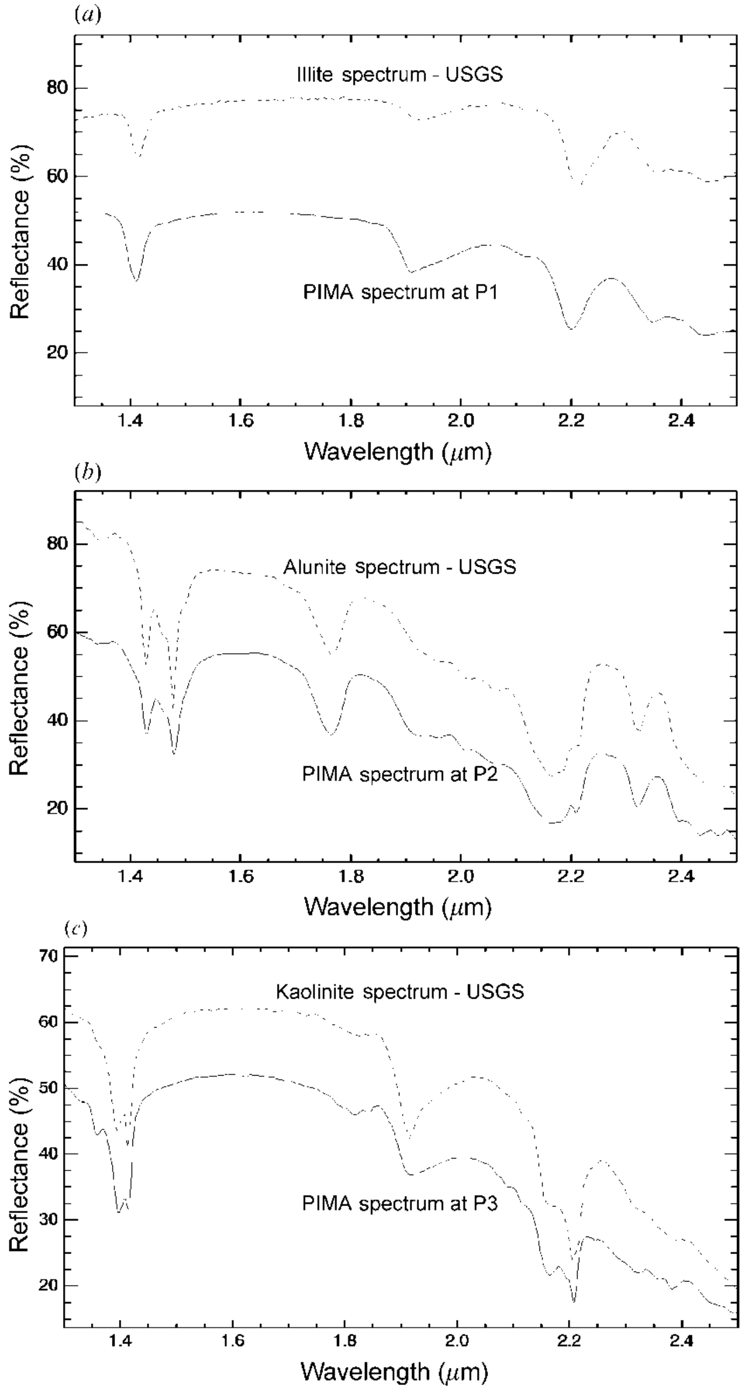

Figure 3. Comparison of spectra collected at sites P1 (*a*), P2 (*b*) and P3 (*c*) (see figure 2 for location) with the spectra of the main minerals identified by the SIMIS spectral analysis package. Field spectra were collected using a PIMA portable reflectance spectrometer. Reference spectra used for the analysis came from the USGS mineral spectra library. Differences in reflectance values between each pair of spectra are due to grain size effects. Spectra from the USGS library, measured from fine grain samples, show higher reflectance values in comparison with PIMA spectra, measured directly from rock samples in the field.

illite (figure 3(*a*)), at P2 as alunite (figure 3(*b*)) and at P3 as kaolinite (figure 3(*c*)). Comparing these results with the RGB image of kaolinite, illite and alunite (figure 2), it is possible to verify that the colour at P1 is yellow, indicating a mixture of illite and kaolinite; at P2 is magenta, indicating a mixture of alunite and kaolinite; and at P3 is red, indicating kaolinite. These results are in agreement with the minerals identified by the PCA method at each site and provide qualitative evidence to support the validity of the method.

Considering the coarse spatial resolution and limited spectral resolution of ASTER imagery, the images presented in figures 1 and 2 are depicting the major mineralogy of the alteration zones at Los Menucos, on a pixel basis over continuous ground surfaces. In fact, the image shown in figure 2 is currently being used in the field as an alteration map to guide exploration activities in the region.

6. Discussion and conclusions

Extracting mineral signatures from high spectral resolution images is not an easy task and usually depends on the availability of specific image processing tools, such as hyper-spectral classifiers and reference spectra. On the other hand, PCA is an easy-to-use technique that has been widely employed for more than a decade and has become a standard in the mineral industry for alteration mapping using Landsat TM.

The results obtained for the Los Menucos area demonstrate that PCA can extract detailed mineralogical information from ASTER multispectral data, in order to produce abundance images for some alteration minerals widely used in exploration for precious and base-metal deposits. This simple, fast and robust technique can also be adapted to bandpasses of hyper-spectral resolution sensors, such AVIRIS, HyMap and Hyperion, for processing large volumes of data worldwide.

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